Paper presented at the International Society of Logistics (SOLE) 1999 Symposium, Las Vegas, Nevada, August 30 – September 2, 1999.

Gas Turbine Engine Health Monitoring and Prognostics

Frank L. Greitzer, Lars J. Kangas, Kristine M. Terrones,
Melody A. Maynard, Bary W. Wilson, Ronald A. Pawlowski,
Daniel R. Sisk, and Newton B. Brown

Pacific Northwest National Laboratory
Richland, Washington 99352

Abstract—A prototype health monitoring and prognostic system for the gas turbine engine on the US Army M1 Abrams tank is discussed. Comprising a set of sensors mounted on the turbine engine, a data acquisition system, and a computer to process the information, the system uses artificial neural networks, rule-based algorithms, and predictive trend analyses to diagnose and predict engine conditions. This paper describes the current status of the operational prototype and assesses potential maintenance and logistics implications of the technology.

Introduction

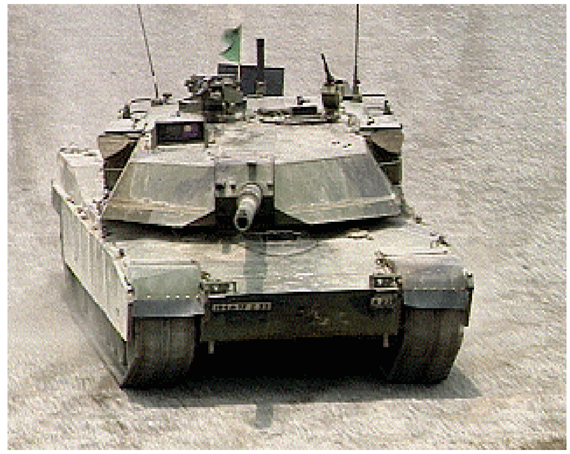
The U.S. Army's current maintenance practices for the M1 Abrams main battle tank (MBT) mainly employ manual diagnostic procedures. Efforts are continually underway to make improvements in materials, electronics/control systems, and automated processes to increase the reliability and performance of the equipment. Nevertheless, current manual processes as well as automated enhancements still generally verify only whether the operational states are within or out of tolerance. For this system, and more particularly for future high-value/high cost vehicles and platforms, there is a need to achieve real-time engine condition monitoring and prediction of near-term vehicle health and readiness. This enhanced technology promises to improve logistics and maintenance processes by enabling reductions in maintenance staff hours, improvements in diagnostic performance, increasing readiness, and providing the information required to optimize maintenance scheduling based on need. This paper describes a current research and development project aimed at fielding a proof-of-concept operational prototype engine health monitoring and prognostic system.

Real-Time Predictive Analysis

Under an Interagency Agreement with the U.S. Army Logistics Integration Agency, Pacific Northwest National Laboratory (PNNL) is developing a prototype diagnostic/prognostic system for the MBT's AGT1500 turbine engine that uses artificial neural networks to diagnose and predict faults. The operational prototype system is called TEDANN, for Turbine Engine Diagnostics using Artificial Neural Networks (Greitzer et al. 1997; Illi et al. 1994; Kangas et al. 1994). The main tasks of the TEDANN project are to develop prototype data acquisition hardware, to design and implement health monitoring software, and demonstrate the proof-of-concept system.

TEDANN will:

- ***Reduce maintenance staff hours***
- ***Improve diagnostics***
- ***Enhance readiness***
- ***Provide for optimized maintenance scheduling***



TEDANN Seeks to Demonstrate an Enabling Technology for Condition-Based Maintenance and Anticipatory Logistics

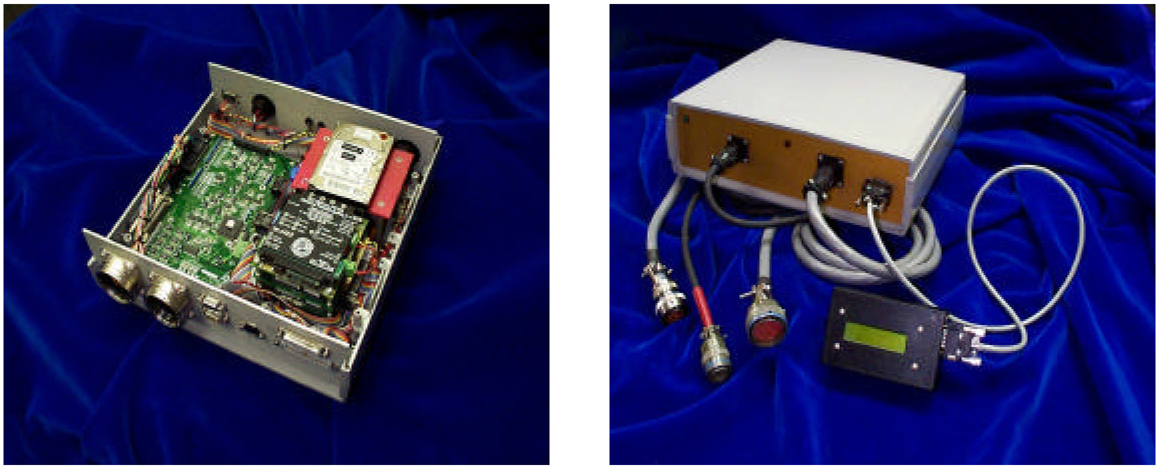
When fully implemented, TEDANN will diagnose/prognose the engine health using onboard sensors. Artificial neural network (ANN) capable of sensor fusion identify deviations from normal operation. Ultimately, fielding this technology in the MBT fleet will enable diagnostic/ prognostic information to be conveyed via telemetry to command/control and maintenance support so that battle readiness and maintenance needs may be assessed immediately.

System Design/Fabrication

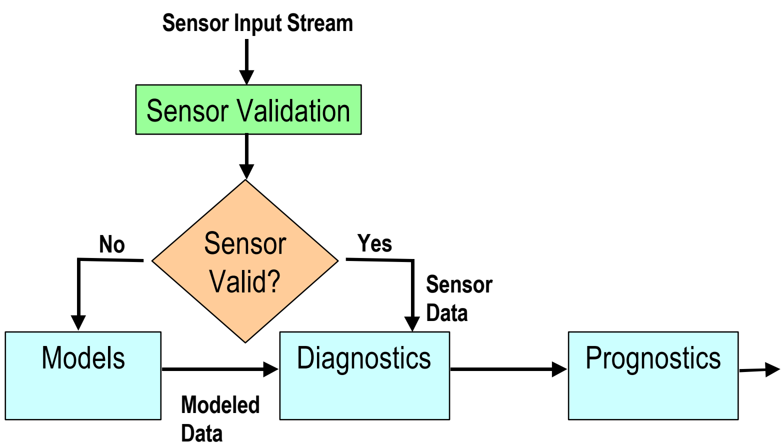
TEDANN receives input from 48 sensors mounted on the AGT1500 engine. Of these sensors, 32 are factory installed for engine control and basic diagnostics performed by the engine control unit. The other sixteen sensors—retrofitted to the engine using a wiring harness—include seven pressure sensors, six temperature sensors, two chip detectors, a vibration sensor and an inclinometer. Advanced microsensor technology has been exploited in this and related projects (Wilson et al. 1999). The thermodynamic (temperature, pressure, RPM, etc.) sensors are located at strategic points along the gas flow in the engine to provide more detailed thermodynamic picture of the engine's state. The TEDANN prototype is contained in an enclosure about one foot square and 3 inches high. The sensor signals are conditioned using two printed circuit boards, multiplexed to a data acquisition card, and then analyzed by a Pentium microprocessor. If fully deployed in the field, the TEDANN system would be integrated with other electronic systems onboard the tank.

TEDANN Analysis

TEDANN is being developed using model-based diagnostics and artificial neural networks. This technology allows the diagnostic/prognostic system to model normal engine performance, learn to recognize deviations from normal behavior, and classify these deviations as conditions requiring maintenance attention.

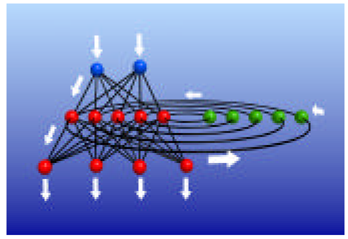


The TEDANN Operational Prototype is Smaller than A Briefcase and Contains Electronics for Data Acquisition, Custom Made Signal Conditioning, and A Multipurpose Computer System



Overview of TEDANN Analysis

The sensor values are first analyzed to determine if they are valid, i.e., within expected operating ranges. If any sensor is determined to be faulty, a modeled value is substituted for the observed value. Artificial neural networks and a set of rules are used to model the sensor values and support sensor validation. Following the sensor validation, the sensor data are processed by diagnostic modules. Diagnostic processing includes rule-based and ANN-based analyses. Rule-based analyses check to see if one or a few sensor values exceed thresholds or fail to follow thermodynamic relationships. ANN-based analyses provide diagnoses of complex faults requiring parallel analysis of a large number of sensors. An unsupervised, self-organizing ANN classifies engine operations into states, such as low-idle, tactical idle, full power, etc. Other supervised, feed-forward ANNs perform engine modeling and pattern recognition to diagnose specific faults and conditions. Such model-based diagnoses are output as parameters that are analyzed in TEDANN's prognostic module.

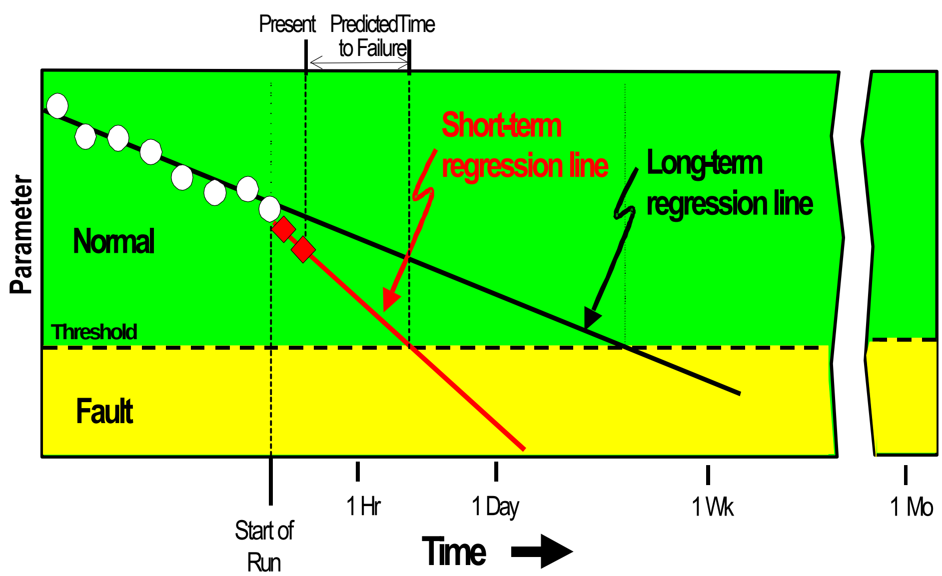


Artificial Neural Networks Model the Engine

Some examples of diagnoses that the TEDANN prototype is being trained to perform are:

Engine Condition	Analysis Approach/Method
Overtemperature	Simple rule
Coking of bearings	Simple rule
Excess metal accumulation	More complex rules or analyses
Low and high-pressure compressor efficiency	Supervised feedforward ANN
Overboard air leakage	Supervised feedforward ANN
Bypass gas leakage	Supervised feedforward ANN

Prognostics—i.e., prediction of faults and degraded performance—is accomplished by trending results from the TEDANN diagnostic module. Both short-term and long-term trends are computed using linear regression on diagnostic values. The system attempts to predict the time until components fail or until engine components will fail to meet specifications. This concept is illustrated in the following figure. More sophisticated statistical techniques are also being investigated (Greitzer et al. 1999).



Predicting Time Until A Failure is Accomplished Using Both Long-Term and Short-Term Trending. The Unfilled Circles Indicate Past Data. The Filled Diamonds Represent Data Obtained in the Current Run.

Field Data Collection

Earlier prototypes of TEDANN have been used to collect data in the field and demonstrate the TEDANN concept. The current version has been installed on six tanks in the field, including US Army National Guard tanks at the Yakima Training Center (YTC) in Yakima, Washington, and US Army test vehicles at the US Army's Yuma Proving Ground (YPG).

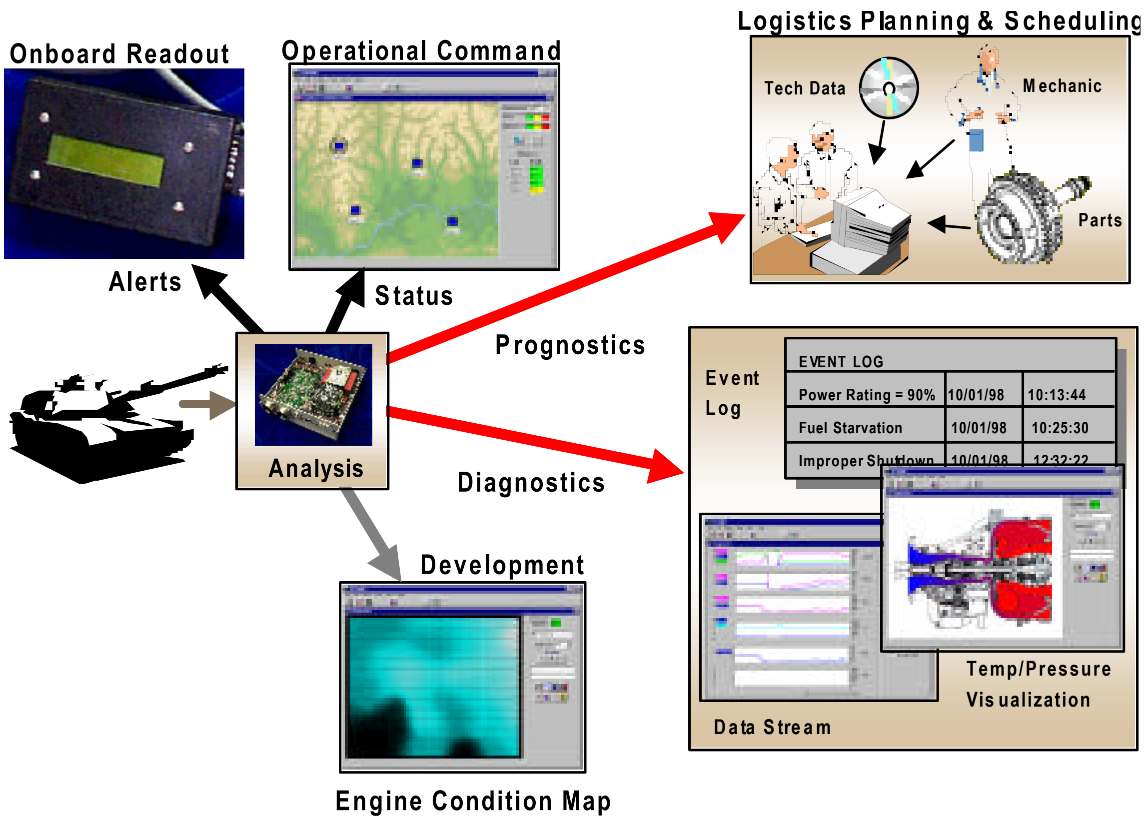
A challenge in fielding the operational prototype hardware has been the equipment variability found among individual tanks. The National Guard tanks are predominantly older models (M1A1s), while the tanks at YPG have all been upgraded in several phases. Two of the four tanks being used for TEDANN data collection at YPG are upgraded M1A1s, and two are M1A2s. The configuration of engine control systems in the tanks varies between M1A1s and M1A2s as well as within these classes of vehicles, especially at YPG where test vehicles are equipped in different ways. The result is that the number of sensors available to the TEDANN units in the various tanks varies considerably, particularly between the M1A1 and M1A2 models. Since a number of faults or conditions are not likely to be observed in our test tanks during the limited data collection period, additional sources of data are used for ANN development and training. The engine manufacturer (AlliedSignal Engines) has provided engine simulation data and test cell data for the AGT1500 turbine engine to supplement the data that are being obtained from the field.

Visualization of Results

Results of the analysis are presented in various forms. For the tank crew, the TEDANN software may display only the most critical information, such as the engine's health check power rating or any critical diagnostic alerts yielded by the real-time onboard analysis. For maintenance personnel, TEDANN displays include graphs of sensor data streams, alphanumeric readouts, an engine duty factor summary, graphical display of temperatures and pressures, and more detailed diagnostic output of the artificial neural network systems. The longer-term vision for a system such as TEDANN is to make higher-level status information available to command center decision-makers (both tactical and logistics/maintenance). Providing status and predictive information in this way will facilitate tactical and logistics planning—for example, enabling tactical commanders to assign vehicles to engagements based on expected operational readiness, and enabling logistics/maintenance planners to schedule maintenance or order replacement parts.

Status

At this time, the TEDANN data acquisition hardware/software is collecting data in the field, the TEDANN system architecture has been developed, and software development is in progress for the final operational prototype. Demonstration of the operational prototype is scheduled for fall 1999.



The Long-Range Operational Concept Includes Information/Status Displays Onboard, at Command Centers, and for Maintenance Personnel to Provide Appropriate Graphical Visualizations of Status, Readiness, and Maintenance Information

Revolution in Military Logistics

To bring about the vision of the Army of the future, new technologies will be developed and exploited to enhance operational readiness and to support rightsizing in force structure and personnel. The logistics community will have to use emerging technologies to make up for the shortfall in personnel, and to help bring about necessary changes in Army doctrine and infrastructure. Traditional stovepipes of Maintenance, Supply, and Transportation must be re-invented and integrated into holistic solutions.

In this view of the future Army, distributed intelligent systems will enable assets to self-report on their status to pre-identified critical nodes, where data are assimilated and sent on to higher-level nodes. Prognostics can provide a rapid assessment of equipment status, and also can identify specific parts that are at risk of failing. This knowledge provides the ability to shift the maintenance paradigm from reactive to proactive—reducing response time, providing appropriate equipment and personnel at the right time and with the necessary tools. Further, prognostics brings the capability to factor in real-time status on the future combat worthiness of forces, prior to committing them to battle.

Bringing about this paradigm shift will require a thoughtful, well-planned, and systematic approach to targeting and developing advanced technologies and, equally important, careful introduction of institutional changes that are required in the practices of the organization, from the field all the way up to strategic/corporate levels.

References

Greitzer, F. L., L. J. Kangas, and M. Melius, LTC, USA. An automated health monitoring system for the Army M1A1/A2 main battle tank AGT-1500 gas turbine engine. *USAF Inaugural Engine Condition Monitoring (ECM) Workshop*, October 21-23, 1997, San Diego, California.

Greitzer, F. L., E. J. Stahlman, T. A. Ferryman, B. W. Wilson, L. J. Kangas, and D. R. Sisk. Development of a Framework for Predicting Life of Mechanical Systems: Life Extension Analysis and Prognostics (LEAP). *SOLE '99 Symposium*, August 31- September 2, 1999, Las Vegas, Nevada.

Illi, O. J, Jr., Major, USA, F. L. Greitzer, L. J. Kangas, and T. Reeve. An Artificial Neural Network System for Diagnosing Gas Turbine Engine Fuel Faults. In *Advanced Materials and Process Technology for Mechanical Failure Prevention: Proceedings, Mechanical Failures Prevention Group Conference*, April 19-21, 1994, p. 359-367. Vibration Institute. Wakefield, Maryland.

Kangas, L. J., F. L. Greitzer, and O. J. Illi, Jr., Major, USA. TEDANN: Turbine Engine Diagnostic Artificial Neural Network. *The American Defense Preparedness Association National Symposium & Exhibition on Advanced Information Systems and Technology for Acquisition, Logistics and Personnel Applications*, March 28-30, 1994. Williamsburg, Virginia.

Wilson, B. W., N. H. Hansen, C. L. Shepard, T. J. Peters, and F. L. Greitzer. Development of a Modular In-Situ Oil Analysis Prognostic System. *SOLE '99 Symposium*, August 31- September 2, 1999, Las Vegas, Nevada.

Acknowledgment

This research and development was conducted for the U.S. Army Logistics Integration Agency under a related services agreement with the U.S. Department of Energy. The Pacific Northwest National Laboratory is operated by Battelle for the U.S. Department of Energy under contract DE-AC06-76RLO1830.

About the Author

Frank L. Greitzer is a Staff Scientist at Pacific Northwest National Laboratory. He holds a BS degree in Mathematics and a PhD degree in Mathematical Psychology. His professional experience includes twenty years of research and development in performance support systems, including artificial intelligence/expert systems applications. Dr. Greitzer is currently the Project Manager for the TEDANN project and Principal Investigator for an internally-funded research and development project called LEAP (Life Extension Analysis and Prognostics), aimed at developing a methodology for predicting the remaining useful life of mechanical systems.